LIGO - T880043

\# 30

List of 3/1/89

LIGO ELECTRICAL POWER

LIGO Engineering Staff
30 November, 1988

1. Introduction

We estimate herein the total electrical power usage of a LIGO installation for the purpose of power capacity planning and cost estimating. We discuss the estimated power needs for lighting, air conditioning (including heating and ventilation), vacuum pumps, electronic equipment, shop equipment, bakeout heaters, and lasers. We have identified several issues requiring further study: allocation for reserve power; power quality, conditioning, and monitoring; power distribution requirements; and back-up and emergency power.

Maximum power requirements are assessed and linearly added together (except as noted below) to determine the installed power capacity requirement. In addition, we have attempted to estimate the average power usage in order to assess probable operating costs.

The results of this study are summarized in **TABLE V.** We conclude that an installed capacity of **~770 kW**, not including an allocation for reserves, is adequate.

2. Lighting

The power required for lighting and utility receptacles is estimated by using simple scaling rules, based upon floor areas, provided to us by a power planning consultant. The floor areas used are based upon present concepts for layout of stations, offices, and shops. Figures 1-4, attached, show the areas used for the corner station enclosure, office/shop areas, and mid- and end-station enclosures. These areas are tabulated and grouped together into categories in **TABLE I.** The scaling rules are enumerated in the text below.

2.1. Offices and public areas:

Use 2 W/ft^2 shielded fluorescent fixtures (50 foot-candles) + 1 W/ft^2 for utility receptacles. Assume **ON** 8 h/day, 260 days per year.

Area = 3300 ft^2
P = 9.9 kW (ON)
P = 2.4 kW (avg.)

2.2. Operations areas:

Use 2 W/ft^2 shielded fluorescent fixtures (50 foot-candles) + 1 W/ft^2 for utility receptacles. Assume ON 24 h/day, 365 days per year.

Area = 1100 ft^2
P = 3.3 kW (ON)
P = 3.3 kW (avg.)

2.3. Shop and service areas:

Use 1 W/ft^2 shielded fluorescent fixtures (25 foot-candles) + 1 W/ft^2 for utility receptacles. Assume ON 8 h/day, 260 days per year.

Area = 4700 ft^2
P = 9.4 kW (ON)
P = 2.2 kW (avg.)

2.4. Experiment and high-bay areas:

In these areas, we propose as a project policy that lighting sources be restricted to incandescent lamps for low RFI. The general strategy is to provide safety-level lighting (so that people don't trip over things) over the entire area during normal working hours and working-level lighting only in areas where work is being done.

Safety lighting: 0.5 W/ft^2 incandescent (3 foot-candles), over entire high bay area plus the areas for experiment electronic equipment (controls and computers) and experiment testing. Assume ON 8h/day, 365 days per year.

Area(high bay) = 19600 ft^2
Area(exp. equip.) = 1584 ft^2
Area(exp. testing) = 1152 ft^2
P = 11.2 kW (ON)
P = 3.7 kW (avg.)

Work area lighting: assume access galleries (12 ft band around entire periphery of high bay area) plus areas associated with one interferometer are illuminated at one time; assume ON 8 h/day, 365 days per year.

WORK AREA LIGHTING

Function	Area *ft^2*	Illumination *ft•candle*	Power *W/ft^2*	P(ON) *kW*
Access galleries	6200	12	2	12.4
Experiment equip.	170	60	10	1.7
Chamber areas	400	120	20	8.0
Laser table area	200	120	20	4.0

Total P = 26.1 kW (ON)
P = 8.7 kW (avg.)

2.5. Mid- and End-station enclosures:

Strategy here is similar to the high-bay area in the corner enclosure. All incandescent lighting is assumed. Safety lighting (2 W/ft^2) is provided for the entire area, similar to the access galleries in the corner enclosure, and work area lighting is provided for individual chamber (20 W/ft^2) and experiment equipment areas (10 W/ft^2). Assume one experiment equipment and chamber area is lighted at one time, and assume that only one mid- or end-station enclosure is being worked in on any given day; assume ON 8 h/day, 365 days per year.

Safety lighting:

Area(high-bay) = 3400 ft^2
Area(exp. equip.) = 1600 ft^2
P = 10.0 kW (ON)
P = 3.3 kW (avg.)

Work area lighting:

Area(chamber) = 200 ft^2
Area(exp. equip.) = 170 ft^2
P = 5.7 kW (ON)
P = 1.9 kW (avg.)

Total P = 15.7 kW (ON)
P = 5.2 kW (avg.)

These estimates are summarized in **TABLE II**.

3. Air conditioning

Heating, cooling, humidity, and particulate matter control power requirements depend upon system requirements, building insulation and sealing properties (capital expenditures), and site environmental parameters. Since we are lacking most of this information at this time, we will assume, as a place holder, a value of 4 W/ft^2 for peak power and assume that the annual average power is about 80% of this value, which is approximately valid for the Edwards site. Using areas from **TABLE I**:

Function:	*Area, ft^2*
Corner enclosure:	
Offices	3300
Operations	1100
Shops	4700
Experiment equip.	1584
Experiment testing area	1152
High bay	19600
	31436
Mid/end-station enclosures:	
Experiment equip.	1600
High bay	3400
	5000
	×4
	20000
TOTAL:	**51436**

Thus, the power required for air conditioning is

$$\mathbf{P = 206\ kW\ (ON)}$$
$$\mathbf{P \sim 164\ kW\ (avg.)}$$

Since this is a major power usage, better estimates are clearly needed; separate estimates are needed for each potential site, and the utilization of waste heat from the lasers for corner station heating needs to be examined.

4. Vacuum pumps

Although vacuum pumps are one of the more important functional elements of the LIGO, their impact on the power design for the LIGO is negligible, as we shall see below. Therefore, we expect that no further work beyond that presented here will be required.

The vacuum pumps naturally divide into two functional areas: roughing pumps, consisting of mechanical and turbo-molecular pumps, and holding pumps, consisting entirely of ion pumps. Pump applications also naturally divide into two areas: pumps for the 2 km tube sections and pumps for the chambers where interferometer equipment is installed. Vacuum pumping strategy will be discussed in detail in an upcoming study of vacuum system configuration; only the salient features necessary for power planning are discussed here.

4.1. Roughing pumps

Each roughing pump set consists of a 300 cfm mechanical pump, a 1000 cfm Roots blower, and a 2200 L/s turbo-molecular pump, which together take a maximum power of **33.2 kW**, not including motor starting requirements. Although one might expect the power to drop substantially as the pressure (load) decreases, this effect turns out to be unimportant and so will not be further considered. To estimate the power requirements for roughing pumps, we consider the following scenarios:

1) Beam tube roughing:

   Upon completion of construction, each 2 km beam tube section will be pumped down for leak checking, using two roughing pump sets (one at each end). It takes about 14 hours to pump down to 10^{-3} torr, so leak checking can begin 24 hours after pumping begins. Assume leak checking of each section takes one month (pessimistic). Pump operation will be intermittent during this time, but we will assume that operation is continuous. After leak-free operation has been obtained and verified, the pumps will be left on, pumping the leak checked section until the pressure reaches $\sim 5\times10^{-6}$ torr, when the ion pumps can be turned on; the pressure will then drop quickly to 1×10^{-6} torr because of the higher pumping speed of the ion pumps. It takes about one month of continuous roughing to reach 5×10^{-6} torr.

   Upon completion of leak checking in the first section, leak checking in the second will proceed. Because leak checking may take substantially less than a month, it is reasonable to assume that a third section could begin leak checking while the first two are still roughing to 5×10^{-6} torr. Thus, six roughing pump sets could be in operation simultaneously, for a total power of **200 kW**. It is conceivable that the fourth tube could be into leak checking within one month of the first, requiring a total power of 266 kW, but it seems highly unlikely. In any case, we will *use the power capacity allocated for the lasers and their cooling*; since this power capacity is likely to exceed even 266 kW, *no additional power capacity is required* for rough pumping of the beam tubes.

   It is interesting to estimate what beam tube roughing might cost. For the above assumptions, each beam tube section would take 2 months × 66.4 kW of electrical power; thus, all four beam tubes would take $\mathbf{3.8\times10^{5}}$ **kW•h**, or about $38K using S.C.E. summer rates.

2) Chamber roughing:

   The same roughing pump sets used for the tube sections are used for roughing the chambers. Assuming that a chamber volume of 500 ft^3 is connected to the roughing pump sets through 200 ft of 24 in ID tubing (628 ft^3), using one roughing pump set it takes about 26 minutes to reach 1×10^{-3} torr. Assuming that the turbo pump speed is 300 L/s at the end of the long roughing tubing, the pumpdown rate is ~5 minutes per decade until the outgassing limit is reached. Assuming that the chambers and roughing connection tubing are cleaned, polished, baked and vacuumconditioned (done at the factory during fabrication) so that the outgassing rate at one hour is 1×10^{-9} torr•L/s•cm^2, then the pressure in an empty chamber is 5×10^{-6} torr after one hour. If a 2000 L/s ion pump (attached to each chamber, see below) is then started and the roughing pumps shut down, the pressure at 1 hour would be 2×10^{-7} torr. Even if the outgassing load of installed interferometer equipment were to exceed that of an empty chamber by a factor of 5, roughing for one hour is *sufficient* to start the ion pump. In the unlikely event that we were to pump down an average of one chamber every day, then

P = **33.2 kW** (during roughing)
P = **1.4 kW** (average)

The peak power may use the power capacity allocated for the laser servicing the chamber being roughed; the average power is negligible.

4.2. Ion pumps

In our current concept of the LIGO vacuum system design, each 2 km beam tube section is pumped by seven 2000 L/s (air) ion pumps and each chamber is pumped by one 2000 L/s ion pump. The following data for a 2000 L/s ion pump is scaled from measurements made on the 400 L/s ion pump used on the LIGO Vacuum Test Facility:

ION PUMP POWER

one 2000 L/s ion pump

Pressure *torr*	Power *W*
10^{-8}	20
10^{-7}	40
10^{-6}	220
10^{-5}	2000

The last line is for completeness only; current planning precludes operation of ion pumps above 10^{-6} torr for other than short periods.

The 28 ion pumps for the beam tube sections will start operating at 10^{-6} torr, for a total power of about **6 kW**, which will decrease steadily with time until the water vapor is gone. Even if the water vapor follows the worst-case prediction in *Livas & Moore* (1988), and nothing is done about it, this power will drop to about 600 W after the first year of operation. The pressure in an empty chamber, as discussed above under *roughing*, drops quickly to ~10^{-7} torr after one hour of roughing, and will reach ~10^{-8} torr after about 20 hours. With the outgassing load of interferometer equipment, it will take longer for the pressure to reach 10^{-8} torr, but the maximum power consumption for the ion pump under any circumstances will be 220 W at 10^{-6} torr. The design and preparation of interferometer equipment will be constrained by the need to reach 10^{-8} torr quickly, because the air lock or gate valve permitting access to the system must remain closed until then to prevent contamination of operating interferometers (this will probably be determined by hydrocarbon contamination considerations rather than water outgassing).

Worst and best cases: With all 59 ion pumps (28 for the beam tubes + 31 for all of the Phase B configuration chambers) operating at 10^{-6} torr, total power is about **13 kW**; with all ion pumps operating at 10^{-8} torr, total power is about **1.2 kW**. Neither case makes a significant impact on LIGO power capacity planning.

4.3. Summary

Beam tube roughing requires a *peak* power of **200 kW**, with a total usage of **3.8×10^5 kW•h** Chamber roughing requires a *peak* power of **33.2 kW**, with an average power of **1.4 kW**. Both peak power requirements can be accommodated within the capacity required for laser power and cooling, and so do not affect power capacity planning. Ion pump power for the beam tubes is initially about **6 kW**, decreasing to a negligible level over the first year of operation. Total ion pump power for the fully operational LIGO is **13 kW** at 10^{-6} torr and **1.2 kW** at 10^{-8} torr.

5. Electronic equipment

This category includes all instrumentation, monitoring, control, data handling and data processing equipment for both the facilities and interferometers. Estimating this major power usage strongly depends on an accurate equipment listing. A strawman equipment list is provided in **TABLE III.** The strawman assumes that a typical rack of equipment uses about one kilowatt. For a "workstation", a Sun 4/110 with a 327 Mbyte disc is assumed. Each "computer" is assumed to be a Sun 4/260 with 32 Mbyte of memory and 2 Gbytes of disc. All equipment is assumed to operate 24 hours per day. The strawman results in a total of **106 kW**. Additional work and inputs are required to refine this estimate.

6. Shop and service equipment

This category includes all machine shop equipment, electronic and vacuum test equipment, and general facility electrical equipment. As in the case of electronic equipment, provision of adequate power capacity for shop and service equipment depends on accurate equipment lists. However, unlike the electronic equipment, most equipment in this category is assumed to be operated with a very low duty cycle. A strawman equipment list is provided in **TABLE IV.** Because of the low duty cycle, nearly random nature of usage of this category of equipment, we have chosen to estimate the required power capacity as the rms sum of the individual items, and the average power usage as the linear sum of the estimated average power for the individual items. While the method of estimating required capacity may seem arbitrary (it is), the convention used by professional power planning strategists is to use 20% of the linear sum of individual items, which would seem woefully inadequate if a single large power item appears in such a list. In any case, the total for this category is relatively small compared to the total capacity requirement, so we will not invest further time in considering the method used for combining these items. Of course, as in the case of electronic equipment, further inputs and better equipment lists are needed to refine the estimates, and the method of combining them may take on greater significance in the future. The strawman results in a total required capacity of **60 kW** and an average power of **27.7 kW**.

7. Bake-out heaters

To estimate the power required for bakeout of vacuum equipment, we make the following assumptions (most will be justified in the upcoming study of the vacuum system configuration):

a) All vacuum surfaces within the station enclosures will need to be baked out initially and from time to time thereafter; there is no need to routinely bake a chamber after each exposure to air. All ion pump bodies will need to be baked out from time to time, including those pumps distributed along the beam tubes.

b) All vacuum surfaces within the station enclosures will be made from prebaked or low hydrogen content steel, so that only H_2O and hydrocarbons need to be removed by bakeout. The maximum bakeout temperature required is 150°C, to remove H_2O; a temperature of ~50°C is sufficient to remove hydrocarbons.

c) Insulation will not be used.

d) Chambers will not be baked out with interferometer components installed.

e) There is no vacuum requirement that all surfaces within an isolated, pumped section of the vacuum system need to be baked simultaneously to remove H_2O; surfaces may be baked in convenient sections.

Assumption (d) allows us to infer that there will always be power capacity reserved for lasers available for vacuum system bakeout. Assumption (e), of course, is key in that it allows us to carve up the bakeout requirements into (nearly) arbitrarily small segments, thereby making the power requirements (nearly) arbitrarily small.

It takes about 100 W/ft^2 to heat an uninsulated stainless steel surface to 150°C, and about 10 W/ft^2 to raise the temperature to 50°C. In the full "Phase B" vacuum system configuration, there are about 14000 ft^2 of vacuum surface in the corner station, and about 2600 ft^2 of vacuum surface in each mid- and end-station. Each ion pump has about 33 ft^2 of surface area. If we assume that we will bake a maximum area of 800 ft^2 at 150°C or 8000 ft^2 at 50°C at one time, then the maximum bakeout power requirement is **80 kW**. This is the power required by one Ar^+ laser, which we propose to steal by shutting down one laser during any major bakeout procedure. We estimate that 24 hours of baking time is sufficient to drive H_2O down to reasonable levels; the required frequency of bakeout is TBD, but might be, say, once per three months of cumulative exposure to air. Bakeout time and frequency required to deal with hydrocarbon contamination depends strongly on history and circumstances. Whether or not bakeouts should be conducted on an *ad hoc* basis or be systematically scheduled is TBD.

We believe that it is practical, through a combination of operating procedures/controls and interferometer design constraints, to reduce bakeout frequency to the point where the above proposal to shut down a laser would be viable. Thus, no additional power capacity would be required.

8. Laser power and cooling

Estimates for laser power are based upon Fred Raab's memo to Bill Althouse dated 18 November, 1988 (attached). That memo concludes that **320 kW** of installed capacity for laser power and cooling is adequate for the life of the facility. To that conclusion, we will propose the additional requirement that the facility design should anticipate future potential upgrade(s) of laser power and cooling capacity.

Average power usage will clearly be time-dependent; for this estimate, we propose that over, say, the first five years of facility life, one pair of Ar^+ lasers will operate essentially continuously, while the second pair (associated with the "development" interferometer) will operate with a 50% duty cycle. Thus, the power required is

$$\mathbf{P = 320\ kW\ (ON)}$$
$$\mathbf{P \sim 240\ kW\ (avg.)}$$

9. Reserve capacity

TBD.

10. Power quality, conditioning and monitoring

TBD.

11. Power distribution

TBD.

12. Back-up and emergency power

TBD.

13. Economics of installed power capacity as a function of time

TBD.

TABLE I

LIGO LIGHTING REQUIREMENTS

CORNER ENCLOSURE AREAS:

	ft×ft	*ft²*
1) Office/public areas:		
Conference room	15×24	360
Director's office	15×18	270
Visitor offices (3)	12×12 (×3)	432
Computer office	12×12	144
Computer user's room	15×21	315
Canteen/kitchen	12×15	180
Emergency/sleeping	12×12	144
Restrooms (2)	12×12 (×2)	288
Lobby, connecting hallways		1170
		3303
2) Operations areas:		
Control room	18×33	594
Computer room	21×24	504
		1098
3) Shop and service areas:		
Mechanical shop	24×33	792
Electronics shop	24×24	576
Receiving area	24×27	648
Inspection area	21×24	504
Cleaning area	18×24	432
Active storage	18×27	486
Clean room	18×24	432
Access hallways		819
		4689
4) Experiment and "high-bay" areas:		
Experiment equip	33×48	1584
Exp. Testing area	24×48	1152
High bay	140×140	19600
Local work areas:		
Access galleries	12×130 (×4)	6240
Exp. equip.	12×14	168
Chamber area	14×14 (×2)	392
Laser table area	12×16	192
Pump stations	14×14	196

MID- and END-STATION ENCLOSURE AREAS:

High-bay	40×84	3360
Exp., system equip.	20×80	1600
Local work areas:		
Exp. equip.	12×14	168
Chamber area	14×14	196

TABLE II

SUMMARY — LIGO LIGHTING REQUIREMENTS

	P(ON) kW	P(avg.) kW
Corner enclosure:		
Offices and public areas	9.9	2.4
Operations areas	3.3	3.3
Shop areas	9.4	2.2
High bay/exp. area safety lighting	11.2	3.7
Work area lighting	26.1	8.7
	59.9	20.3
Mid- and end-station enclosures:		
Safety lighting	10.0	3.3
Work area lighting	5.7	1.9
	15.7	5.2
TOTAL	**75.6**	**25.5**

TABLE III

LIGO ELECTRONIC EQUIPMENT POWER REQUIREMENTS

	racks *@1 kW*	*workstations* *@1.5 kW*	*computers* *@3 kW*	**Power kW**
CORNER ENCLOSURE EQUIPMENT:				
Common facilities:				
Vacuum system monitoring and control	1	1		2.5
Housekeeping and security monitoring	3	1		4.5
Data recording	2	1		3.5
Data processing		1	1	4.5
Workstation servers			2	6.0
Communications and other services	2		1	5.0
Total, common facilities	8	4	4	26
Interferometers:				
Each interferometer	(6)	(2)		(9.0)
Total, 6 interferometers	36	12		54
Total, corner enclosure	44	16	4	80
EACH MID- and END-STATION ENCLOSURE:				
Common facilities:				
Housekeeping, vacuum system control, communications & local displays	2	1		3.5
Interferometers:				
Each interferometer	(1)			(1.0)
Total, 3 interferometers	3			3.0
Total, each mid/end enclosure	5	1		6.5
Total, 4 mid/end enclosures	20	4		26
TOTALS:	**64**	**20**	**4**	**106**

TABLE IV

LIGO SHOP AND SERVICE EQUIPMENT POWER REQUIREMENTS

	Operating Power *kW*	Duty Cycle *%*	Average Power *kW*
CORNER ENCLOSURE EQUIPMENT:			
Machine shop equipment:			
Drill press	0.8	4	0.0
Band saw	6.6	0.5	0.0
Welder	46.0	0.5	0.2
Grinder	0.7	0.5	0.0
Sander	1.2	0.5	0.0
Ultrasonic cleaner	1.8	4	0.1
Vented fume hood	1.4	4	0.1
General service equipment:			
Monorail crane (5 ton)	7.5	~0	0.0
Bridge crane (10 ton)	11.3	~0	0.0
Laminar flow bench (2)	2.6	100	2.6
Vacuum cleaner	1.2	0.5	0.0
Vacuum oven	6.0	15	0.9
Testing area vacuum chamber pumps	10.0	~0	0.0
Air compressor	4.0	20	0.8
Hot water heater	6.0	10	0.6
Telephone control system	1.5	100	1.5
Copy machine	1.8	25	0.5
Intercom	0.2	100	0.2
Mass spectrometer	1.2	100	1.2
Oscilloscopes (4)	0.8	25	0.2
Total, Peak Power (rms sum)	51		
Total, Average Power			8.9
EACH MID- and END-STATION ENCLOSURE:			
Monorail crane (5 ton)	7.5	~0	0.0
Bridge crane (10 ton)	11.3	~0	0.0
Laminar flow bench	1.3	100	1.3
Vacuum cleaner	1.2	0.5	0.0
Vacuum oven	6.0	15	0.9
Air compressor	4.0	20	0.8
Intercom	0.2	100	0.2
Totals, each mid/end enclosure:			
Peak power (rms sum)	16		
Average power			4.7
Total, 4 mid/end enclosures	31		18.8
TOTALS:	**60**		**27.7**

TABLE V

SUMMARY — LIGO POWER REQUIREMENTS

Ref. §		Maximum Power *kW*	Average Power *kW*
1.	Lighting	76	26
2.	Air conditioning	206	164†
3.	Vacuum pumps:		
	Beam tube roughing	200*	‡
	Chamber roughing	33*	1
	Ion pumps (first year of operation)	6	
	Ion pumps (fully operational)		1
4.	Electronic equipment	106	106
5.	Shop and service equipment	60	28
6.	Bake out heaters	80*	—
7.	Lasers (including cooling)	320*	240
8.	Reserve	TBD	TBD
	TOTAL	**768**	**566**

*Will not operate simultaneously; only largest is included in sum.

†Place-holding estimates; further work required; site-dependent (Edwards estimates are shown).

‡3.8×10^5 $kW{\cdot}h$ total.

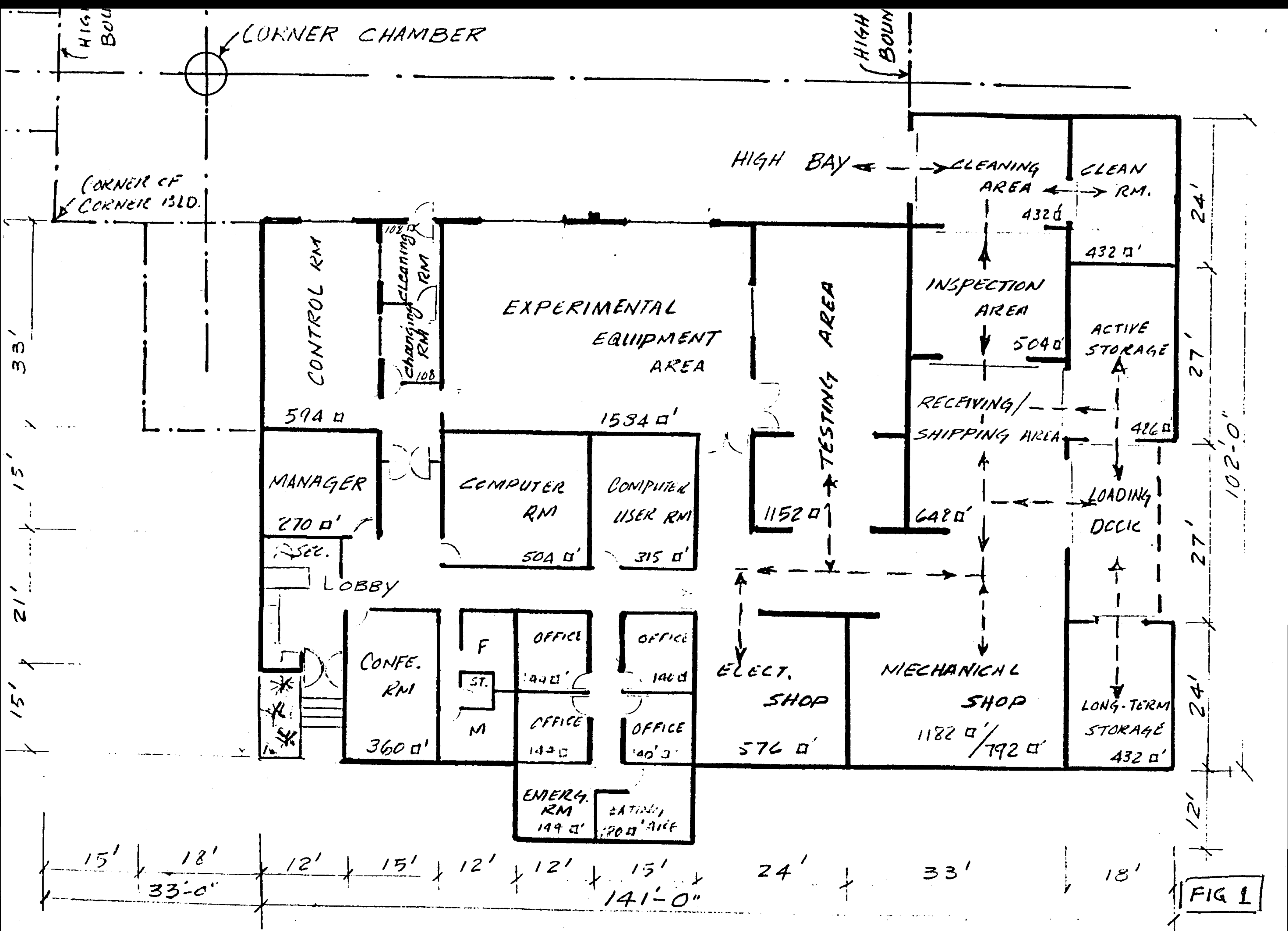


FIG 1

TOTAL SQ. FT ≃ 12,000

FLOOR PLAN OF OFFICES & SHOPS

TBA
10/28/77

F.B.A.
8/31/58
Rev. 1

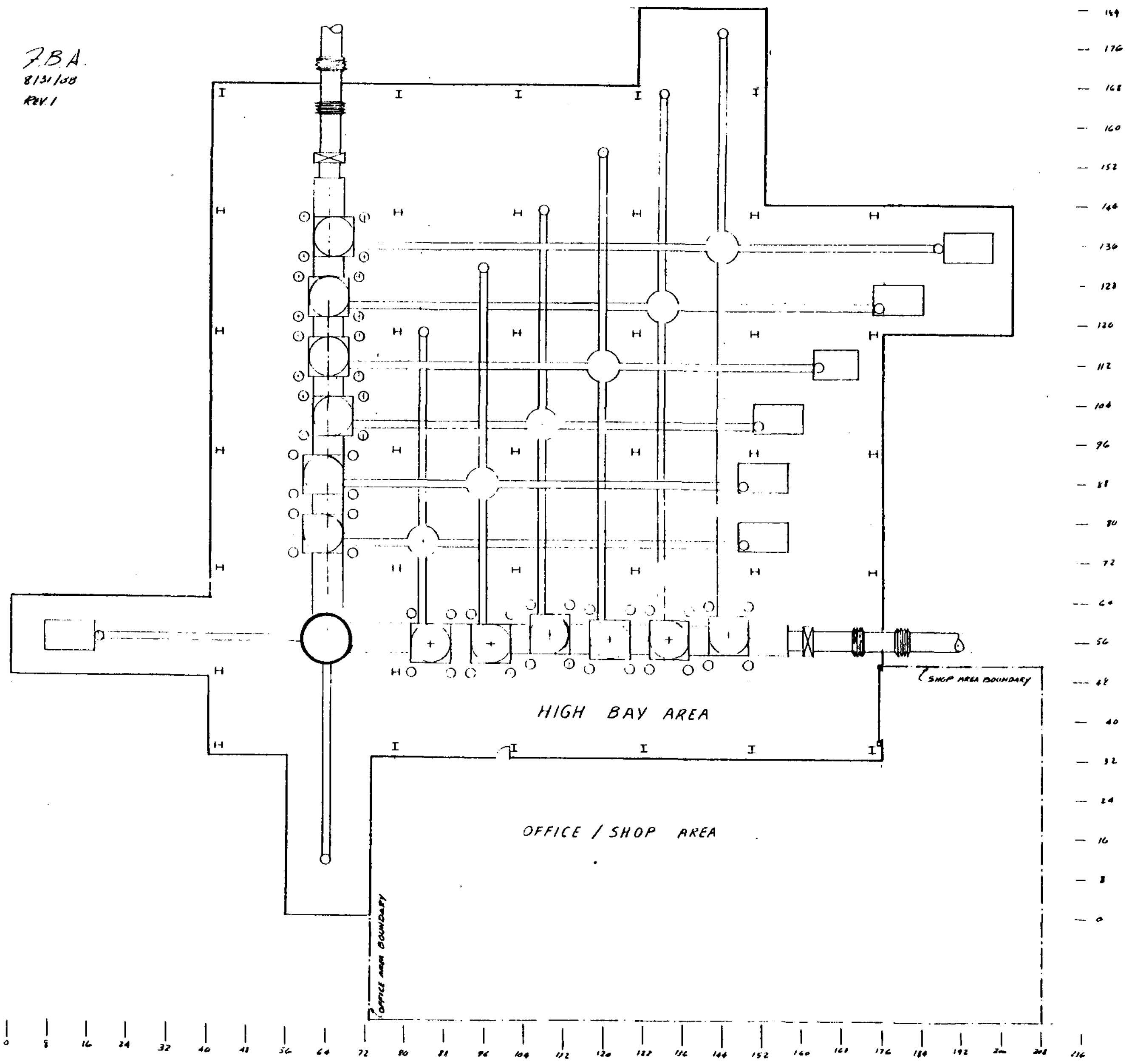
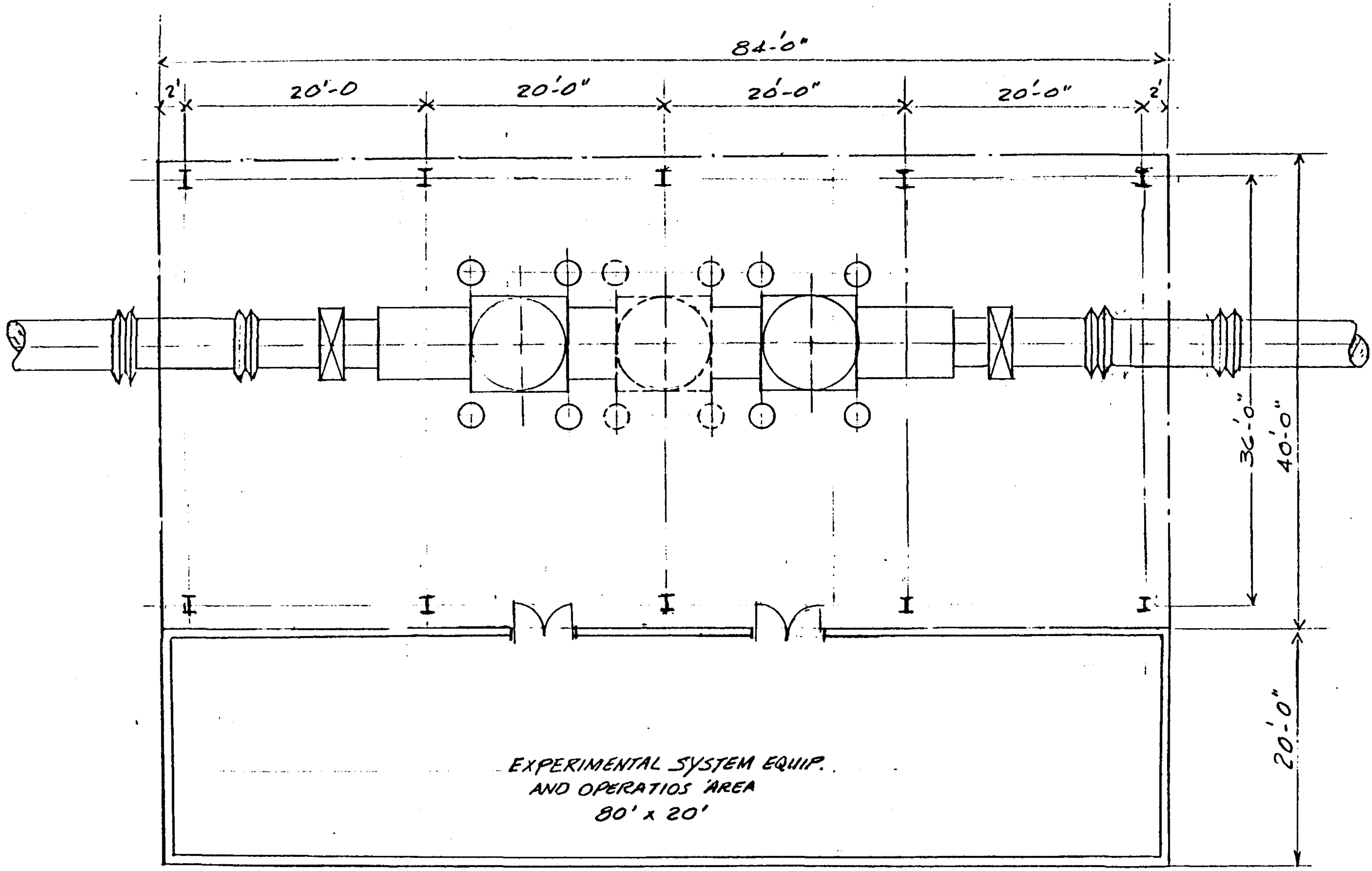


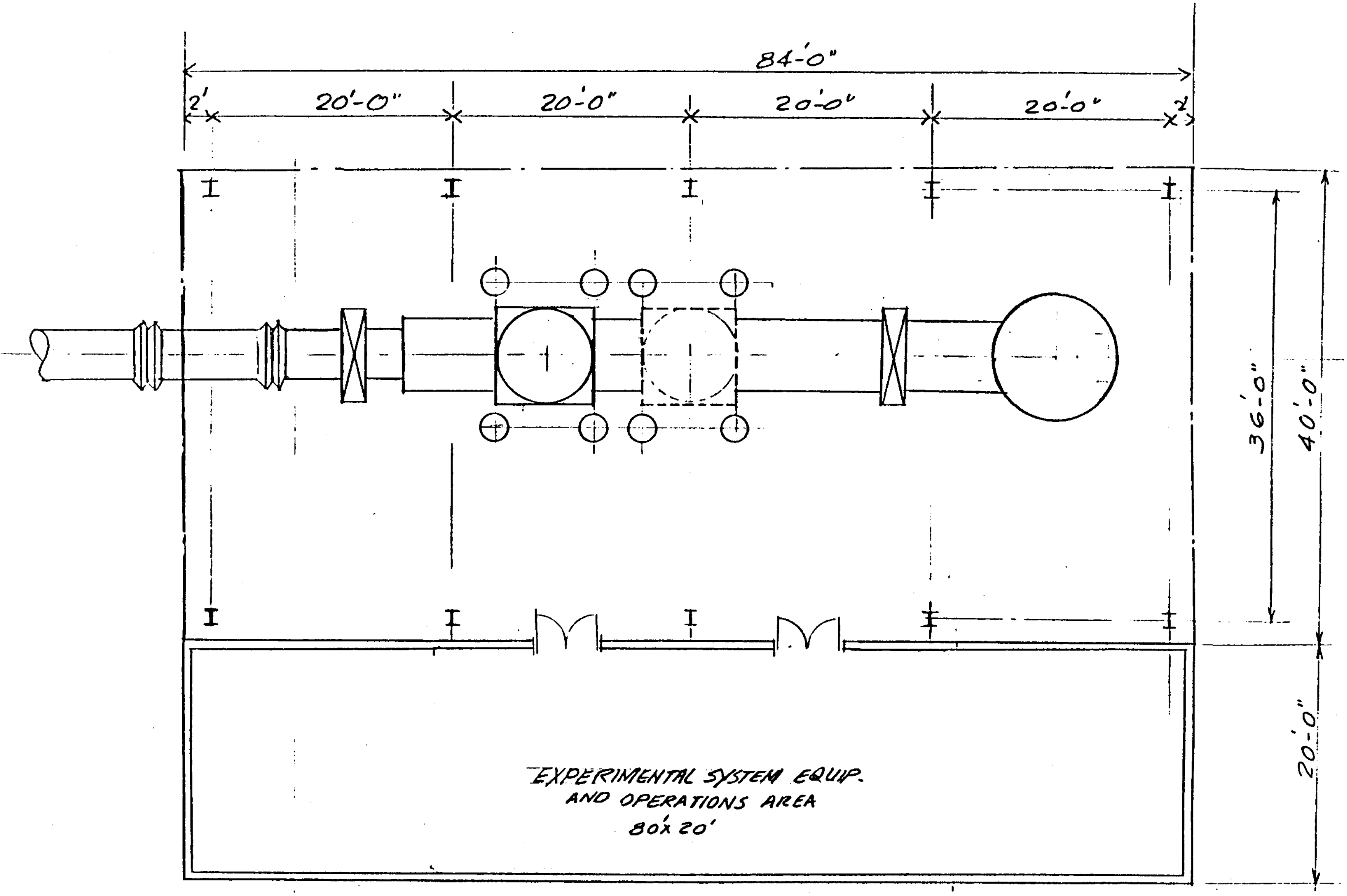
FIG. 2



FLOOR PLAN OF MID-STATION
SCALE 1/8" = 1'-0"

FBA
REV. 1
12/1/88

FIG. 3



FLOOR PLAN OF END-STATION
SCALE 1/8" = 1'-0"

7BA
REV. 1
12/1/88

FIG. 4

To: Bill Althouse
From: Fred Raab, 18 November 1988
Subject: Specification for Laser Power/Cooling

Laser Power/Cooling Specification:

Each LIGO site will require 320 kW of electrical consumption to be dedicated to laser power and cooling.

Rationale:

This number represents the peak demand for laser power/cooling which should serve the facility over its 20 year lifetime. This number is based on an operations scenario which includes a phase A plan, during which discovery of gravitational waves is accomplished, and a phase B, during which the facility evolves into a national astronomical facility.

I have assumed that during phase A each site will operate two detectors, each consisting of a full-length and a half-length interferometer. One detector will be dedicated to gravity wave searches and the second will be used for research and development (R/D) of future detectors. The first task for phase A after construction will be to install the first detector and get it operational. This detector will certainly use large frame Ar^+ lasers, each unit requiring 80 kW of electricity for power and cooling.

I assume that within the early years of operation Nd:YAG lasers become available which run TEM_{00}, SLM, producing green light with a conversion efficiency of 2%. (For diode pumping and doubling the theoretical limits are 3.5% to 7.0% (see Rai's memo on laser power).) The peak demand during phase A is determined by when the switchover to YAG technology occurs. From Vogt's discussion with Byers at Stanford (unmemoed) it appears possible that such lasers, capable of producing 100W of green light, will be ready in time to be incorporated into the second LIGO detector. In this scenario we would have two Ar^+ lasers in one detector (160 kW total) and two YAGs in the second (15kW total) for a total power/cooling consumption of 175kW. A two site LIGO could then reach shot noise limited performance down to the Standard Quantum Limit (SQL) at frequencies below 50 Hz, assuming 100ppm mirrors and a 50% coupling efficiency into the interferometers.

However, the first R/D detector will have to be designed well before the first detector is fully operational, and YAG technology may not yet be ready for inclusion in the first generation of R/D detectors. In this case the facility may need two more Ar^+ lasers for the second detector, or a total of four such lasers which would require 320kW for power/cooling. This is a worst case scenario. Nonetheless, under the assumptions in the previous paragraph, a two site LIGO could reach SQL at 10 Hz.

The 320kW electrical specification should be adequate throughout the phase B stage of the LIGO. It provides the possibility of running six 700W green output YAG lasers to run three detectors in the astronomical facility mode. Assuming only 25% coupling efficiency and 100ppm mirrors, each of the detectors would be capable of outperforming the advanced detector curve in the Dec87 proposal.

Warning:

The perfomance levels quoted above assume the accuracy of Kip's estimate of shot noise limited burst sensitivity for a recycled interferometer. Rai's estimates give poorer performance by $2^{1/2}$. I have done an estimate which agreed with Kip's but Martin Regehr has found some errors in my work. This issue must be resolved before the construction proposal is written. However I believe this is a second order issue. The power capacity needed at installation is determined by practical issues. The YAG developments then will lower the electrical demands of installed lasers, probably into phase B. The advanced detector's performance depends on a number of parameters such as mirror losses which cannot be extrapolated 20 years into the future. Even if all factors go against us, if we are successful with our work and good physics requires an incremental dose of power, I believe we can get it.